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Process Control Applications of Adaptive λ-Tracking

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Abstract

In this paper we present three applications of adaptive λ-tracking that show the suitability of this control method for industrial process control problems. The λ-tracker is a simple design/low complexity adaptive controller that is universal in the sense, that no process model or plant tests are required for the controller design. Furthermore, the controller exhibits remarkable robustness properties. We briefly review the theory of adaptive λ-tracking, and discuss advantages and shortcomings of this method.

1 Introduction to adaptive λ-tracking

The control problems that typically appear in the process industries can be roughly divided into two categories: Firstly, control problems that require complex controllers in order to accomplish the desired control tasks. For example, strongly interacting multivariable processes typically belong to this class, or processes with very challenging specifications on the control performance to be achieved. The total number of these control problems is however relatively small when compared to the total number of control problems in a typical plant (in [13] it is estimated that less than 5% of all industrial process control problems do belong to this class). The second category of industrial process control problems is characterized by the fact that simple control structures, like P- or PI-controllers, are sufficient to achieve the desired control performance. Typically underlying level, flow or sometimes temperature controllers belong to that class, and mostly the main goal is a stabilization and setpoint control of the process. Very often there are hundreds of loops of this kind, even in relatively simple plants.

Virtually all advanced controller design techniques focus on the first category of control problems. In general the controller design is based on a suitable model of the process and a high degree of control theoretical expertise and experience is typically required to design and maintain these types of controllers ("Ph.D.-controllers"). In addition implementation of these feedback strategies is often very involved, and expensive hard- and software is required. This all adds up to significant capital and personnel costs that drastically limit the number of control loops that can get this type of attention.

For the second type of control problems no process model will be available in general and the controller parameterization will be done by process engineers using tuning rules and experience. Due to changes in the operating conditions or changes in parts of the plant these controllers do need frequent re-tuning, otherwise bad performance or even instability may occur. In any case, there is no assurance for the stability of the closed loop other than experience based on similar control problems from the past.

In this paper we discuss the application of the recently developed adaptive λ-tracking controller ("adaptive λ-tracker") to industrial process control problems. This controller combines simple design and implementation with novel control theoretic methods that allow to guarantee stability and performance in a robust way. This combination makes this control methodology especially well suited for the second category of industrial control problems described above.

The concept of λ-tracking (or λ-stabilization) [9, 11] differs only slightly from the normal definition of tracking and stability. Here, the output is no longer controlled to a setpoint, but rather to a λ-neighborhood of the setpoint (or the reference trajectory to be tracked), where $\lambda > 0$ is an arbitrarily small but fixed prespecified maximal error. In other words we want to guarantee that the measured output $y(\cdot)$ asymptotically satisfies

$$|y(t) - y_{ref}(t)| \leq \lambda \quad \text{for} \quad t \to \infty\,,$$

with $y_{ref}(\cdot)$ denoting the (time-varying) reference signal or the constant setpoint. In addition the controller has to guarantee that all states are bounded. Thus the goal of adaptive λ-tracking is rather basic and reduced to the essential needs of many industrial control problems. The advantage of this simple objective is threefold: The desired control goal can be achieved by a very simple adaptive control structure and the specifications can be achieved in a very robust way for a large class of nonlinear plants. Furthermore no model of the plant and no on-line tuning is needed to derive the controller parameters and no re-tuning is necessary when operating conditions change.

The structure of the adaptive λ-tracker is essentially that of a simple P-controller with a time-varying gain $k(\cdot)$:

$$\boxed{\begin{aligned} u(t) &= -\beta \cdot k(t) \cdot \Big[y(t) - y_{ref}(t)\Big] \; + \; \delta \\ \dot{k}(t) &= \begin{cases} \gamma \Big(y(t) - y_{ref}(t)\Big)^2 & \text{, if } |y(t) - y_{ref}(t)| \geq \lambda \\ 0 & \text{, if } |y(t) - y_{ref}(t)| < \lambda. \end{cases} \end{aligned}} \tag{1}$$

The gain $k(t)$ is strictly monotonically increasing as long as the difference between the output $y(t)$ and the reference signal $y_{ref}(t)$ is larger than the given λ. If this difference enters the λ-strip the adaptation is switched off and the gain is kept constant. The parameter β, that either takes the value plus one or minus one, has to be chosen positive if the high-frequency gain of the plant is positive and negative if the high-frequency gain is negative. In case of unknown high-frequency gain this feedback can be extended to adaptively determine the correct sign [2]. Independent of the choice of the design parameters $\lambda > 0$, $\gamma > 0$ and δ, this control law achieves λ-tracking for a large class of nonlinear processes. The assumptions on this class are essentially that the plant considered is globally minimum phase (no inverse response behavior) and that the system has a relative degree of one. An extension to the multivariable case can be found in [3, 6].

There are three tuning parameters that can be used to "customize" the feedback for the application at hand. These parameters have a very transparent meaning and their choice is in general straightforward. Parameter λ is clearly related to the desired performance in that it specifies the maximal allowable control tolerance. Parameter γ adjusts the speed of adaptation and a sensible choice lies in the order of magnitude of the inverse of the dominant time constant of the plant. It is easy to see from the control law, that parameter δ should be chosen as the value of the estimated steady state input value at the main operating point.

The adaptive λ-tracker has by now been applied to a range of processes, among others several chemical and biochemical reactors and a biogas tower reactor for yeast production at the *Deutsche Hefewerke* in Hamburg, Germany. After a short review of the main theoretical results in Section 2, the remainder of this paper is devoted to these applications, where we critically discuss merits as well as shortcomings of this approach.

2 Review of some theoretical results

In this section we briefly review the theory of adaptive λ-tracking for nonlinear systems. We consider nonlinear SISO-system that are given in or can be transformed to the following form:

$$\begin{aligned} \dot{y} &= f(y, \boldsymbol{z}) + g(y, \boldsymbol{z}) \cdot u \\ \dot{\boldsymbol{z}} &= \boldsymbol{h}(y, \boldsymbol{z}) \end{aligned} \tag{2}$$

with $\boldsymbol{z} \in \mathbb{R}^{n-1}$, $u \in \mathbb{R}$ being the manipulated input and $y \in \mathbb{R}$ being the measured and controlled output. The state dimension n needs not be known and we need to make no assumptions about the steady state equilibrium $(y_e, \boldsymbol{z}_e, u_e)$. We make the following assumptions about nonlinear system (2):

Assumptions

(A1) The zero dynamics $\dot{\boldsymbol{\eta}}(t) = \boldsymbol{h}(y_e, \boldsymbol{\eta}(t))$ of system (2) are globally exponentially stable at $\boldsymbol{\eta} = \boldsymbol{z}_e$.

(A2) System (2) has strong relative degree one and moreover $g(\cdot,\cdot)$ is bounded away from zero and either positive or negative, i.e. there exists a $\sigma_1 > 0$ such that

$$\begin{aligned} & g(y, \boldsymbol{z}) \geq \sigma_1 && \forall\,(y, \boldsymbol{z}) \in \mathbb{R} \times \mathbb{R}^{n-1} \\ \text{or}\quad & g(y, \boldsymbol{z}) \leq -\sigma_1 && \forall\,(y, \boldsymbol{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}\,. \end{aligned}$$

(A3) f, g and $\boldsymbol{h}$ are affine linearly bounded, i.e. for some unknown constants $M_f, M_g, M_h > 0$ we have

$$\begin{aligned} |f(y, \boldsymbol{z})| &\leq M_f \left(\left\| \begin{smallmatrix} y \\ \boldsymbol{z} \end{smallmatrix} \right\| + 1 \right) && \forall\,(y, \boldsymbol{z}) \in \mathbb{R} \times \mathbb{R}^{n-1} \\ |g(y, \boldsymbol{z})| &\leq M_g \left(\left\| \begin{smallmatrix} y \\ \boldsymbol{z} \end{smallmatrix} \right\| + 1 \right) && \forall\,(y, \boldsymbol{z}) \in \mathbb{R} \times \mathbb{R}^{n-1} \\ \|\boldsymbol{h}(y, \boldsymbol{z})\| &\leq M_h \left(\left\| \begin{smallmatrix} y \\ \boldsymbol{z} \end{smallmatrix} \right\| + 1 \right) && \forall\,(y, \boldsymbol{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}\,. \end{aligned}$$

From an application point of view, Assumptions (A3) can be considered as a "technical assumption". Assumption (A2) means that the high-frequency gain g is either 'positive' or 'negative'. It is merely required that g will not change sign anywhere. This is a rather strong assumption that essentially excludes the presence of any singular points in the whole state space. The strongest assumption, and the most difficult to verify, is (A1).

Theorem 2 ([2, 6]) *Suppose $\gamma > 0$ and β is chosen such that it has the same sign as $g(y, \boldsymbol{z})$. For any system (2) satisfying (A1)-(A3) the application of the adaptive feedback (1) permits for arbitrary initial conditions $[y(0), \boldsymbol{z}(0)]^T$ and $k(0)$ a solution to the closed-loop system that exists for all times and every solution has the following properties:*

(i) The gain $k(t)$ does not grow unbounded, i.e. $\lim_{t\to\infty} k(t) = k_\infty$ exists and is finite;

(ii) all states remain bounded: $y(\cdot), \boldsymbol{z}(\cdot) \in L_\infty(0, \infty)$;

(iii) $y(t) - y_{ref}(t)$ approaches the interval $[-\lambda, \lambda]$ as $t \to \infty$.

Theorem 2 states that for any nonlinear system satisfying assumptions (A1)-(A3) λ-tracking or λ-stabilization is achieved and that the adaptation converges.

Assumptions (A1)-(A3) can be relaxed and the class of systems for which feedback law (1) works is actually bigger than the one described. It has for example been shown that the same simple feedback also achieves λ-tracking for classes of distributed parameter systems [7], for nonlinear time-varying systems [2] and for linear sampled systems [10]. In case the high-frequency gain is unknown, feedback (1) can be extended such that this case is also covered [2]. In addition the feedback can be reformulated such that a polynomial upper bound on f (instead of an affine linear bound as in (A3)) can be considered [6]. Note, that controller (1) exhibits remarkable robustness properties in that it achieves λ-tracking for a whole class of systems, namely all systems for which Assumptions (A1)-(A3) are satisfied. Also note, that this controller is *not* a model-based controller and no tuning, except for the choice of parameter γ, is needed. See [2] for a detailed discussion of further properties of this adaptive control law.

3 Process applications

Adaptive λ-tracking has by now been applied to a wide variety of process control problems both in simulation and in experimental studies. In this section we want to exemplary report about three process control applications that allow to judge the achievable performance with the

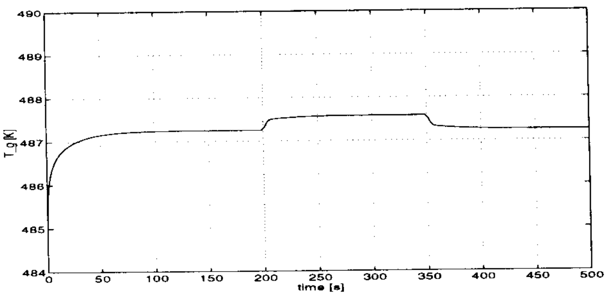

Figure 1: Closed-loop behavior of controlled output T_g of the methanol reactor with adaptive λ-tracker.

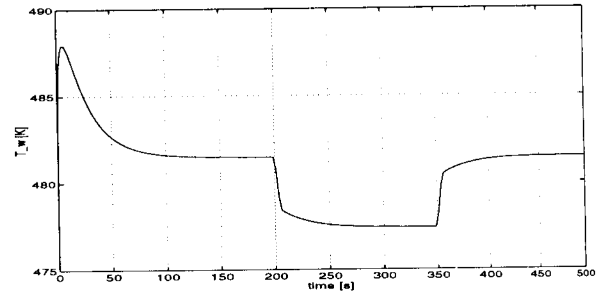

Figure 2: Closed-loop behavior of manipulated input T_w of the methanol reactor with adaptive λ-tracker.

adaptive λ-tracker and to discuss different aspects of this control methodology. The first two applications are simulation studies for a SISO and a MIMO control problem, while the third application describes an experimental implementation at an industrial pilot plant.

3.1 Control of a CSTR for methanol synthesis

In this section, we report about the application of feedback law (1) to a realistic CSTR control problem. The process we are studying is methanol synthesis in a polytropic, catalytic continuous stirred tank reactor on solid phase catalyst. The reversible exothermic reaction considered is given by a complex kinetic scheme following a four step mechanism with realistic parameters. The model and data are taken from [5] and [14] and are based on the "UCKRON-1" test problem for reaction engineering modeling that we extend to form a realistic control problem. The control objective is to avoid thermal runaway by maintaining the gas phase temperature T_g in the reactor at a desired level despite disturbances in the feed. The reactor is very sensitive to these disturbances, where the feed temperature T_g^{feed} must be considered as having the main influence. In open loop, disturbances by as little as 1% result in thermal runaway and eventually destruction of the catalyst. The coolant temperature T_w is used as the manipulated variable u. Hence we have a SISO control problem.

We consider two different models for this process: a rather simple model of order three that is known to describe the structural properties of the reactor dynamics sufficiently well. Based on this model satisfaction of assumptions (A1)-(A3) can be shown [2]. The second model is a detailed model of order nine, that describes the true dynamical behavior of the real reactor in a very good way and will be used to represent the real plant when testing the controllers in simulation. For a description of these models see [2, 14]. Fig. 2 shows the gas phase temperature T_g in the closed-loop, when the λ-tracker with $\lambda = 0.3[K]$, $\gamma = 1[\frac{1}{K}]$, $\beta = 1$ and $\delta = 480[K]$ is applied to the detailed model of the reactor. The initial conditions of the detailed model are not at steady state and no disturbances are applied during the first 200 seconds. It can be seen, that within one minute the gas temperature reaches the desired level without overshoot. At time t = 200 seconds, a significant disturbance of +7% is applied to the feed temperature T_g^{feed} and taken back at time t = 350 seconds. Fig. 1 shows that the controlled output only changes its value within the control tolerance of $0.3[K]$. Fig. 2 displays the necessary input moves in T_w. The controller was also tested with other disturbances, measurement noise, additional parameter uncertainties, and for the task of tracking a reference trajectory. In all cases completely satisfactorily performance as for the disturbance described above could be observed. In [2] the performance of the adaptive λ-tracker is compared to the performance achieved with a advanced nonlinear state feedback controller based on I/O-linearization. For this application both schemes lead to a similar level of performance for the relevant disturbances. However a major advantage of the λ-tracker is that the control law is very easy to design and implement and that stabilization and λ-tracking is achieved in a very robust way.

3.2 Control of a binary distillation column

We consider control of a binary distillation column with 40 trays, that is used for high-purity separation of methanol and 1-propanol. An inferential control scheme is applied where two temperatures T_{14} and T_{28} in the rectifying and stripping sections of the column are measured and controlled to setpoint. As manipulated inputs the reflux stream L and the vapor stream V leaving the reboiler are used. We have thus a MIMO control problem with two inputs and two outputs. Control of distillation columns is still considered a challenging problem as this process is highly nonlinear and very sensitive to disturbances. An additional problem comes from the fact that neither the exact structure nor the parameters of a distillation column model are usually known exactly. The most simple mathematical model for this distillation column, based on material balances alone, consists of 42 nonlinear differential equations. In order to apply adaptive λ-tracking, assumptions (A1)-(A3) have to be satisfied. To show that this is the case for a nonlinear system of order 42 (having a zero-dynamics of order 40) is not a straightforward task. It must be clear that a rigorous mathematical proof cannot be given for all assumptions. This is a rather typical situation for industrial applications of adaptive λ-tracking. Here, for example the relative degree assumption is straightforwardly satisfied. The main difficulty lies in showing global exponential stability of the zero-dynamics. This is virtually impossible. However, using a combination of physical insight into the process and system theoretic analysis it is possible to "gain confidence" that this assumption is indeed satisfied for the inferential control configuration used. (cf. [1]).

The controller used is a straightforward MIMO extension of the one introduced in the introduction. Details can be found in [3]. The closed-loop performance is investigated in simulations where a more detailed model of the distillation column, that consists of a set of 248 differential algebraic equations, is used to represent the real plant. The true dynamics of a real column is fairly well described by this model.

Fig. 3 and 4 show the two temperatures T_{14} and T_{28} to be controlled and the manipulated variables L and V for the closed loop with the MIMO λ-tracker and the detailed distillation model. After 1000 seconds a large disturbance of +15% in the feed flow rate and at time $t = 2000$ seconds in addition a disturbance in the feed concentration of +20% was applied. At $t = 3000$ seconds the feed flow rate and feed concentration were taken back to normal level. As can be seen, the adaptive controller attenuates the disturbances in a absolutely satisfying way, and stays within the desired λ-strip of $\pm 1K$, without requiring any excessive moves in the manipulated variables. The same level of performance is also achieved for other disturbances or set point changes. This performance is again comparable to the one achieved with advanced nonlinear control strategies like I/O-linearization [4]. This shows that even difficult MIMO control problems can be solved satisfactorily with the λ-tracker. However, we want to stress, that in this case we have no absolute guarantee in form of a rigorous proof, that this scheme will work globally for the distillation column as it is not possible to rigorously validate the assumptions.

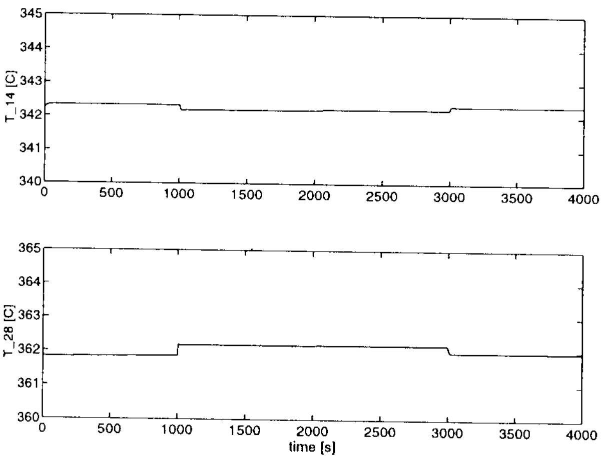

Figure 3: Closed loop behavior of the distillation column with adaptive controller (time response of temperatures T_{14}, T_{28}).

3.3 Control of a biogas tower reactor

In this section, we describe application of adaptive λ-tracking to the control of a biogas tower reactor in pilot plant scale that is located at the Deutsche Hefewerke (DHW) in Hamburg, Germany. The reactor is used for treatment of anaerobic waste water that comes from a yeast production plant and contains sulphuric acid and

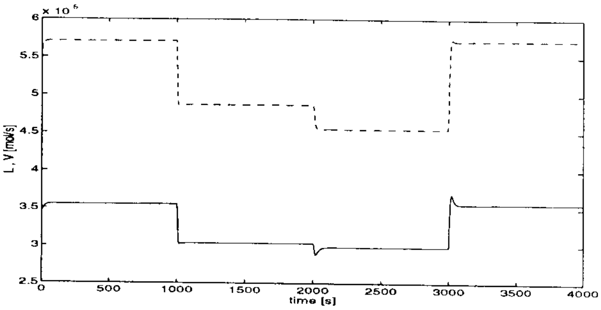

Figure 4: Manipulated variables corresponding to Fig. 3; dashed: boilup stream V, solid: reflux stream L.

organic compounds. The waste water is fed into the biogas tower reactor, where via microorganisms a mesophile anaerobic biochemical conversion of the organic influent compounds takes place. The reactor, which is 20m high and has a diameter of 1m, consists of four identical modules, each similar in structure to an airlift loop reactor, that are arranged as a tower on top of each other. The waste water stream with flow rate f_{feed} is split up into four influent streams with flow rates $f_{feed,i}$, where the i-th stream is fed to the i-th module. These inflow rates are the four manipulated variables u_i. The four controlled variables y_i are the pH–values in each module that are measured on–line. The reactor is open-loop unstable and described in detail in [12].

In [12] a simple model of order four is developed for the reactor, that is used to check assumptions (A1)-(A3). It turns out that the reactor satisfies all assumptions except for (A2) and thus the standard λ-tracker cannot be applied. It can however be shown [8] that an extension of the simple λ-tracker with the following physically motivated nonlinear feedback law

$$
\begin{aligned}
u_1(t) &:= \tfrac{k(t)}{y_1(t)-y_{feed}}(y_1(t) - y_{ref,1}),\\
u_2(t) &:= \tfrac{k(t)}{y_2(t)-y_{feed}}(y_2(t) - y_{ref,2}) - \tfrac{y_2(t)-y_1(t)}{y_2(t)-y_{feed}}\, u_1(t),\\
u_3(t) &:= \tfrac{k(t)}{y_3(t)-y_{feed}}(y_3(t) - y_{ref,3}) - \tfrac{y_3(t)-y_2(t)}{y_3(t)-y_{feed}}\, [u_1(t) + u_2(t)],\\
u_4(t) &:= \tfrac{k(t)}{y_4(t)-y_{feed}}(y_4(t) - y_{ref,4})\\
&\quad - \tfrac{y_4(t)-y_3(t)}{y_4(t)-y_{feed}}\, [u_1(t) + u_2(t) + u_3(t)],
\end{aligned}
$$

together with the standard adaptation law for the gain $k(t)$ as in (1), achieves λ-tracking and convergence of the adaptation. This feedback law can be viewed as a cascade of a nonlinear compensation, that renders assumptions (A1)-(A3) satisfied, and an (almost) standard λ-tracker.

The control law with parameters $\gamma = 0.002$, $\lambda = 0.05$, and $y_{ref} = [6.9, 6.975, 7.075]^T$ was implemented on a DCS using a discrete integration algorithm with a sampling time of 6 minutes. For this experiment only modules 1-3 where considered and used.

Figure 5 shows experimental data for the pH-values y_i that were obtained at the pilot plant when the above "extended" λ-tracker was applied. The controller was switched on at time $t = 48h$. It can be seen that without controller the pH–values drift away. Within only 24 hours after switching the λ-tracker on the pH-values are brought back to the desired λ-strips, that are depicted by the cross-hatched areas in Fig. 5. Like for the other appli-

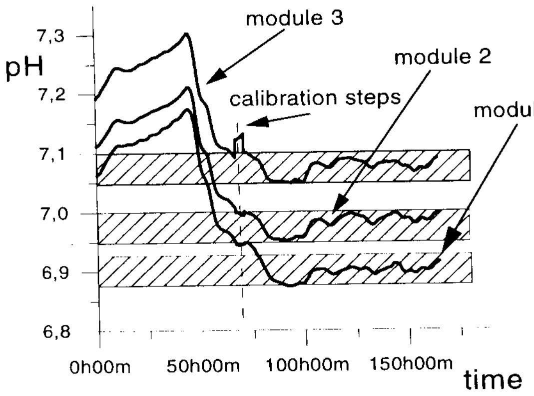

Figure 5: Stabilization of pH-values in the biogas tower reactor (experimental results).

cations the gain parameter k only rises to a modest level ($k=0.08$).

This application shows that even in the case when not all λ-tracking assumptions are satisfied for the original plant, suitable application dependent extensions can be found such that the λ-control concept can still be applied successfully.

4 Discussion and conclusions

With the process control applications described in this paper we want to show that adaptive λ-tracking is a well suited control scheme for a large class of industrial process control problems. The λ-tracker combines two favorable aspects: Firstly, the controller has a very simple structure, needs (virtually) no tuning, is very easy to implement, and exhibits remarkable robustness properties. Secondly, a rigorous mathematical proof of robust λ-stabilization and tracking and of convergence of the adaptation is available, together with a clear characterization of the necessary assumptions that need to be satisfied. It must be clear that the λ-tracker is not an all purpose tool. There are many control problems for which this approach will not lead to satisfying results. Especially,

- if the assumptions are not satisfied,
- if there is severe measurement noise,
- if there are high demands on the control performance,
- if a suitable and exact model for a model-based controller design is available,

then one should refrain from applying the λ-tracker. However, this approach is especially attractive,

- if no process model (or no suitable model for model-based controller design) is available,
- if the process description is highly uncertain and/or highly nonlinear,
- if the main goal is to keep some variables within bounds,
- if fast time-constants or restrictions in the process control hard- or software prevent application of complex controllers.

For practical applications the λ-tracker can and must of course be extended for example by an interlock structure. It is also useful to extend the adaptation mechanism by various heuristics, for instance, that the value of the gain parameter k is reset from time to time.

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